TRANSITION TIME FROM RESISTIVE TO SUPERCONDUCTING STATE FOR THIN INDIUM FILMS

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ABSTRACT

If a superconducting thin indium film carrying a steady d.c. current is given a pulse of current of sufficient magnitude to create a magnetic field that destroys the superconducting properties, the film becomes resistive. When the pulse of current is terminated, there is an appreciable time lag until the thin film again becomes fully superconducting. This transition time from the resistive to the superconducting state has been termed the "backswitch" time.

This investigation explored some of the characteristics of the backswitch time, particularly its behavior under conditions of changing input pulse height, d.c. reference current, temperature, thin film thickness, and thin film substrate. Two thin tin films were also briefly examined. The data obtained proved to be very consistent and the general behavior of backswitch time was established.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1. Introduction

The phenomenon of superconductivity, that is, that certain elements and alloys at very low temperature exhibit no resistance to an electrical current, has been investigated for many years. So far no complete theory has been accepted to explain the anomalous behavior. However, a large array of facts have been gathered since Kamerlingh Onnes discovered superconductivity in 1911. The authors hope that this thesis may add yet another place to the puzzle which will someday be fully solved.

Although it was known that the electrical resistance of most metals decreases with temperature, it was not until helium had been liquified and thus even lower temperatures reached that the discovery was made that the resistance of some metals completely disappears above $0^{o}K$.

The behavior of superconducting metals under the influence of a magnetic field has been an area of particular interest. It has been found that the temperature at which a particular metal becomes superconducting is a function of the magnetic field around the superconductor. This function has not, as of this date, been completely determined, although there is evidence[1] that it approaches a relationship $H/H_o = 1-(T/T_c)^2$ (see Fig. 1).

One of the fundamental properties of all superconductors in the so-called "Meissner effect". This is the property that when superconducting, the metal is impermeable to magnetic flux. This means that as a current flows in a superconductor, it must be a surface or "skin" effect rather than an internal current. Actually, it has been found that there is a "penetration depth", varying with temperature, for the magnetic flux, and

[1] D. Shoenberg, Superconductivity, Cambridge Press, pp. 8-10, 1952

that the magnetic flux presumably falls off exponentially from the surface. For indium, one of the most important superconductors, this penetration depth is of the order of 6×10^{-6} cm. at 0^{o}K.

In the study of superconductors in a magnetic field it is often advantageous to utilize specimens which consist of thin films of indium or tin. In general, one technique of making these thin films is to evaporate the indium or tin under high vacuum (about 10^{-7}mm. of Hg.) onto glass or quartz substrates. Two razor edges are adjusted to control the film width which is of the order of 40 to 60 microns. The amount of material evaporated determines the thickness, normally about 600 Å. and up. The glass or quartz substrates are cut into flat discs about one inch in diameter. This type of thin film element is of convenient size for handling experimentally with the equipment used (to be described later).

One method to produce magnetic fields around the superconductor is to pass a direct current through the thin film. If the current is increased with temperature remaining constant, a field of sufficient magnitude is finally created that destroys the superconducting properties and the thin film then becomes resistive. This is called "forward switching". Decreasing the current will then cause the element to "backswitch" to the superconducting state. The temperature at which the element becomes superconducting with zero magnetic field is called the critical temperature (T_c). At any temperature below T_c, the current necessary to provide sufficient magnetic flux to cause the thin film to forward switch is called the d.c. critical current (I_c). A plot of I_c versus temperature gives a curve roughly similar to Fig. 1.

If a thin film receives, while superconducting and carrying a steady d.c. current below I_c, a pulse of current such that the sum of the pulse

and the steady d.c. current exceeds I_c, the film switches resistive, then back to superconducting as the pulse rises and falls. It is an observed phenomenon that the potential difference across the thin film does not follow the input current pulse. It takes an appreciable time to forward switch to fully resistive, then again exhibits a time lag when it back-switches to fully superconducting. This behavior is shown in Fig. 2 in which the current pulse is indicated as the input pulse and the potential difference across the thin film as the output. Upon termination of the input pulse, the potential difference across the thin film corresponds to the product of the steady d.c. current and the thin film resistance measured at liquid helium temperature. This potential difference remains constant for a period then falls off to zero as the element returns to the fully superconducting state. The time from the termination of the input pulse until the potential difference across the element falls to zero is indicated as the backswitch time. The detailed kinetics of this time lag are not understood and no validated theory exists to explain the phenomenon.

2. Equipment

The mechanical equipment used in this investigation was primarily for the regulation of temperature. Liquid helium was used to reach the temperatures necessary for tests. The temperature was controlled by varying the vapor pressure of the helium. The heart of the entire system is the automatic regulator valve designed by E. C. Crittenden. This regulator contains a valve attached to a rubber diaphragm floating on a variable amount of mercury. The amount of mercury under the diaphragm controls the pressure at which the valve opens to permit the vacuum pump to take a suction on the helium vapor. The level of the mercury in the float chamber is varied by raising or lowering a mercury reservoir connected to the float chamber by a rubber tube. As the vapor pressure over the liquid helium builds up, the valve opens and permits the excess vapor to be drawn off until the preset level is again obtained. Hence, the vapor pressure over the helium and the temperature of the helium are held to very close tolerances. The vapor pressure is measured directly by means of a mercury manometer. The small end of the manometer is attached to a small vacuum pump and evacuated to effectively zero pressure. The other end of the manometer is open to the vapor pressure of the helium in the cryostat. The vapor pressure is read directly as the pressure differential of the manometer. A semi-block diagram of the physical arrangement is shown in Fig. 3.

The nature of the electrical measurements to be made required a variable direct current supply, a source of square wave pulses and a means of observing the behavior of the thin film element.

A variable d.c. power supply of standard construction was utilized. The current from this source maintained a reference current in the

element under test.

A Teletronics PG 200 AA pulse generator was used as a square wave source and to provide sweep synchronization signals for the oscilloscope. This pulse generator has variable pulse amplitude, duration, and repetition frequency.

The oscilloscope used to view the thin film behavior was a Tektronix Type 541 with a 53/54C dual-channel preamplifier unit installed, permitting input and output traces to be observed simultaneously. This oscilloscope was equipped with a Polaroid Land camera in order that oscillographs could be made. All backswitch data was recorded photographically to permit subsequent careful examination and analysis.

The thin film element holder was made to fulfill the specific purposes of this investigation. The dimensions were determined by the element and cryostat size. Lead (Pb) strips were bolted to the plastic holder to form contact strips for the thin film. Coaxial 50-ohm leads for the d.c. reference level current, output voltage, and the input pulse were attached to these lead strips. A 50-ohm terminating resistor for the input pulse cable was made from a piece of one-mil nichrome wire. The resistance of nichrome at liquid helium temperatures is essentially the same as at room temperature. Fine copper wire was twisted together and wired to the element holder to cancel out the electromotive force associated with the system inductance. A block diagram of the electrical system and a drawing of the thin film element holder are included in Figs. 4 and 5.

3. Experimental Procedures

Before immersing the specimen holder containing the thin film element in liquid helium it was first necessary to precool it carefully. A too rapid lowering of temperature may cause the glass or quartz substrate to crack, or cause stresses to be set up in the thin film which would then flake off or fracture. This precooling consisted first in placing the element holder in liquid air vapor for several minutes and then very carefully dipping the element holder into the liquid air until it had reached liquid air temperatures. The element was then left in the liquid air until ready to transfer it to the cryostat. All pieces of equipment which would at any time be in contact with liquid helium were first precooled with liquid air. When all was in readiness, the element holder, hanging from the coaxial cables, was placed inside the cryostat which was then bolted into position on the test stand; next came the Dewar flask filled with liquid air into which the cryostat was immersed. The liquid helium was then transferred from its storage container into the cryostat by means of a precooled transfer tube. Transfer completed, the tube was removed and the transfer hole plugged. Then, as was described earlier, the vacuum pump was started to carry off the evolved helium gas and to maintain whatever vapor pressure was desired by means of the automatic regulator valve. This completed the preliminary phases of the experiment.

In order to conduct a study of the backswitching characteristics of various thin films, a decision had to be made as to what variables to use. It was decided to vary the pulse height, the d.c. reference current level at which the film would be pulsed, and the temperature. This meant holding the pulse duration and the pulse repetition frequency constant. A convenient value of 20 microseconds was chosen for the pulse duration and

a value of 150 pulses per second for the repetition frequency. In this region, backswitch time was found to be independent of the pulse duration and repetition frequency.

At some chosen temperature in the superconducting region, various d.c. reference current levels below the d.c. critical current (I_c) were selected. At each d.c. reference current level a series of photographs were taken of the oscilloscope traces with gradually increasing input pulse heights, controlled by the square wave pulse generator. The d.c. reference current levels were set and maintained from a rectified d.c. power supply. Since the oscilloscope traces gave readings in potential difference, it was necessary to calibrate the scope for each thin film in order to be able to convert the potential difference readings to current readings. This was done at a temperature above T_c by measuring (with a milliammeter) the current required from the d.c. power supply to raise the output trace on the scope 1 cm., then measuring the height of the input pulse necessary to raise the output trace the same amount (1 cm.). This gave the conversion from input potential difference to input current.

The thin films chosen for use in these experiences (tabulated in Table I) had already been the subject of investigation by other research workers and much was known regarding their behavior, but no measurements had been made of their backswitching characteristics. In all cases previous data gathered on these films were checked and found to be quite precise. Then, further measurements were made to determine the backswitching characteristics, as described above.

4. Experimental Results

In all cases, as input pulse height from a constant d.c. reference current was increased, the backswitch time went from zero to some maximum value, then decreased to a minimum value, then increased again. Curves of backswitch time versus input pulse heights above various d.c. reference current levels for each element are contained in Figs. 7 to 18. These curves start at the maximum time for each d.c. reference current, except when otherwise noted.

At a given temperature the backswitch times between the maximum and minimum values are essentially independent of the d.c. reference current level. That is, the same input height at different reference current levels produced the same backswitch time, as can be seen from Figs. 7 to 18.

When an element is pulsed at constant temperature, the maximum backswitch time for each d.c. reference current level always occurs at the same value of pulse height above I_c. It is to be noted that a constant value of pulse height above I_c is equivalent to a constant value of total current passing through the element. This information is displayed in Fig. 19.

The maximum in backswitch time increases as the d.c. reference current level increases, becoming infinite at some value less than T_c.

The minimum backswitch times were all on the order of one to two microseconds, regardless of temperature, d.c. reference current level, element resistance, or pulse height involved.

At any temperature in the superconducting region, there is a value of d.c. reference current less than the d.c. critical current, at which the entire element switches resistive when pulsed and remains resistive.

This value of reference level is very difficult to determine accurately since the element is very unstable in this region. The value is considerably dependent on the rate at which the pulse height is increased.

A comparison of elements Q-9 (quartz substrate, Figs. 17 and 18) and 64 (glass substrate, Figs. 9 and 10), which have nearly the same dimensions and resistance, shows that nearly identical backswitch times exist in the maximum-minimum range. However, the entire range of maximum backswitch times at various d.c. reference levels for element 64 is much greater than for element Q-9.

Elements Q-8 and Q-9 (Figs. 15, 16, 17, 18), differing only in thickness, produce curves of backswitch time versus pulse height above d.c. reference current level that are nearly identical in shape. However, the higher resistance element (Q-8) requires less input pulse height from the same d.c. reference current to reach the same backswitch time. It is noted, however, that Q-8 has a lower I_c than Q-9 at the same temperature and thus requires less input pulse to forward switch it.

If the temperature of any particular element is reduced, for a given d.c. reference current, less input pulse height is required to produce the same backswitch time, but again the curves are nearly identical in shape.

Two thin films made of tin were included in the investigation, but very little data could be obtained from them and no curves were plotted. The range of backswitch times from maximum to minimum were only on the order of from two to three microseconds, and this range was passed through with but a small increase in pulse height. Furthermore, this range was passed through well before the element had fully forward switched, making analysis difficult.

In the region of backswitch time beyond the minimum value, it is

noted that the higher the d.c. reference current level, the sharper the rise of backswitch time with increasing input pulse height. In the elements with a quartz substrate (Q-8 and Q-9) the backswitch time increases slowly with increasing input pulse height after the minimum time has been reached (See Figs. 15, 16, 17, 18).

5. Conclusions

The results of this investigation are very consistent. The reported facts were observed without contradiction in all of the indium elements tested. While the backswitch phenomenon is undoubtedly complex, it is, however, qualitatively predictable and quantitatively reproducible.

The behavior of the backswitch time is characterized by two regions; the first, in which the potential difference across the film is constant and equal to the product of the film resistance and the d.c. reference current, and second, when the potential difference decreases to zero, presumably as the film makes the transition across the phase boundary of Fig. 1 (intermediate state). Thus the element appears to remain fully resistive for a part of the backswitch time. The element has been driven resistive by increased magnetic field and is then warmed by Joule heat until equilibrium is reached. When the pulse is removed, it seems reasonable to assume that the resistance begins to decrease when the phase boundary of Fig. 1 is reached. If one further assumes that the magnetic field falls to its final value (due to the d.c. reference current) before appreciable cooling occurs, one may discuss the backswitch phenomenon as primarily a heat conductor problem. Suppose, while resistive, the element is heated to a temperature such that the d.c. reference current exceeds I_c for that temperature. When the input pulse is terminated, it takes time for the element to cool to a temperature where the d.c. reference current equals I_c for that temperature. This would account for the constant potential part of the output pulse during the backswitch. As the element begins to go superconducting at the phase boundary, the potential difference across the film falls off and the film temperature further decreases to that of the liquid helium.

On that basis, one would expect the backswitch time to increase with increasing pulse height from a constant reference level, but such is not the case. As was stated in the previous section, the time rises to a maximum, decreases to a minimum, then increases again. It would be difficult to explain the anomalous behavior of decreasing time on a heat conduction basis without postulating the existence of some sort of thermal phenomenon in connection with the thin film and liquid helium, in which an increase in Joule heat to the thin film (from increasing input pulse height) would cause the film to cool more rapidly when the pulse was terminated. It appears doubtful that such a thermal phenomenon exists. The cause for the decrease in backswitch time with increasing pulse height will probably be found through consideration of other factors such as the decay of the magnetic induction in the thin film. There are many consistencies in the heat conduction theory, however, and they will be discussed in subsequent paragraphs.

It is known that there is some optimum value of input pulse height above I_c, equivalent to a total current through the element during the pulse, that produces a maximum in backswitch time (See Fig. 19). It is further known that this maximum time decreases as the d.c. reference current is lowered. This appears reasonable since the heat produced in the film after the termination of the input pulse (due to the I^2R from the d.c. reference current) would be less at lower d.c. reference currents and the film would therefore cool faster.

On this basis one would expect that for elements of equal resistance, a quartz substrate would produce shorter maximum backswitch times than a glass substrate since quartz is a much better heat conductor than glass. Thus the film evaporated on quartz would cool much faster than one with a

glass substrate. A comparison of elements Q-9 (quartz substrate) and 64 (glass substrate) shows this to be confirmed (See Figs. 9, 10, 17, 18).

Further consistency is shown by a comparison of elements similar except for resistance, such as Q-8 and Q-9. The element with the lower resistance (Q-9) has the higher value of I_c for a given temperature. Thus, a higher input pulse is required to switch the element resistive. To produce the same backswitch time, Q-9 must be given a higher input pulse than Q-8. This is reasonable since the lower resistance would require a higher current to produce an equivalent I^2R (See Figs. 15, 16, 17, 18).

The analysis of the effects of reducing the temperature are somewhat more complex. Since it is presumed that the I^2R through the film during the time of pulse duration determines how high the temperature of the film is raised, the same input current to a film at a lower initial temperature should raise its temperature to a lesser value than if it were pulsed at a higher initial temperature. Therefore, the backswitch time should be shorter when an element is pulsed at a lower temperature from the same d.c. reference current level. This follows since after termination of the input pulse, the film would more quickly reach the temperature or field at which the d.c. reference current equals I_c for that temperature. Experimental results show that the backswitch time is indeed shorter when a film is pulsed identically at a lower temperature.

The tin elements tested produced extremely short backswitch times. Insufficient data was obtained to base any conclusions other than that tin has characteristics very different from indium.

It was found that if the d.c. reference current was raised high enough (but still well below I_c) that an element when pulsed would not backswitch,

but remain resistive. It appears that this phenomenon is caused by the I^2R from the d.c. reference current being so high that the film is unable to cool to a temperature where it can go superconducting and is thus maintained in the resistive state.

It is possible that the minimum values of backswitch time for a given element are all dependent on the same value of input height above I_c, similar to the maximum time dependence. It was found experimentally that in the region of minimum backswitch time, a large change in input pulse would cause a very small change in backswitch time. Therefore, a small error in detecting the point of minimum time could cause a large error in the associated input pulse height. The results obtained from the photographically preserved data are very inconsistent in this case because of this. At the minimum, practically all of the time was in the resistive region with only a small part in the intermediate region. Another contradiction to the heat conduction theory appears here in that the minimum times were all on the order of one to two microseconds, regardless of temperature, d.c. reference current level, element resistance, or pulse height involved.

The weight of evidence indicates that while heat conduction may be an important factor in the backswitching behavior of thin film, there are other complex factors such as the magnetic field behavior involved that serve to cause the anomalous behavior observed.

6. Recommendations for Further Work

There are several other facets of the backswitching phenomenon worthy of investigation:

1. Test elements of the same resistance, but with different film widths to see if width of the film is a variable factor in the backswitch time.
2. Use a signal generator allowing variable rise time for the pulse to determine the effect of pulse rise time on the backswitch time.
3. Determine the variation of backswitch time with pulse duration using short pulses in the area of one microsecond.
4. Investigate backswitch time using negative d.c. reference current levels.
5. Use superconducting metals other than indium for the thin films and determine if there is a relationship between their thermal conductivities and their backswitching characteristics.
6. Determine what relationship exists between the forward switching characteristics and the backswitching characteristics of an element.

The writers wish to express their appreciation for the guidance and encouragement given them by Professors J. N. Cooper and E. C. Crittenden of the U. S. Naval Postgraduate School, and for the technical assistance proferred by Mr. K. C. Smith, also of the U. S. Naval Postgraduate School.

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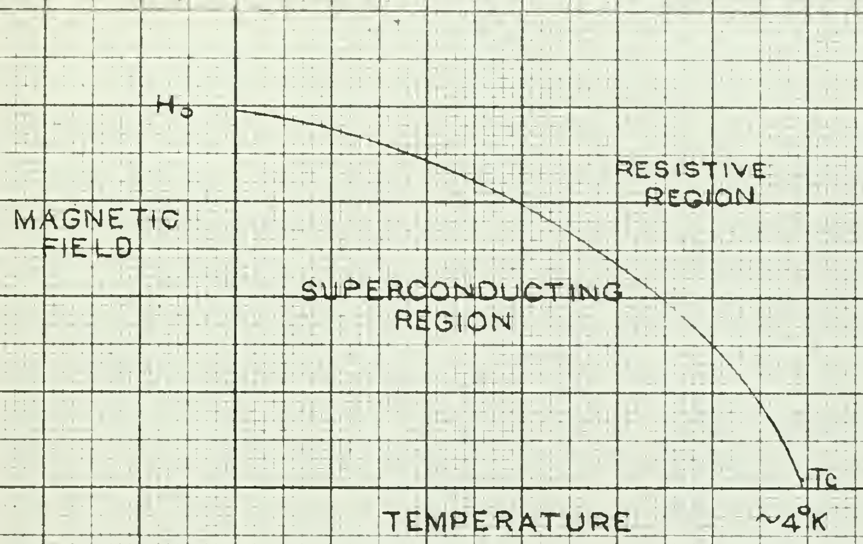


FIGURE 1

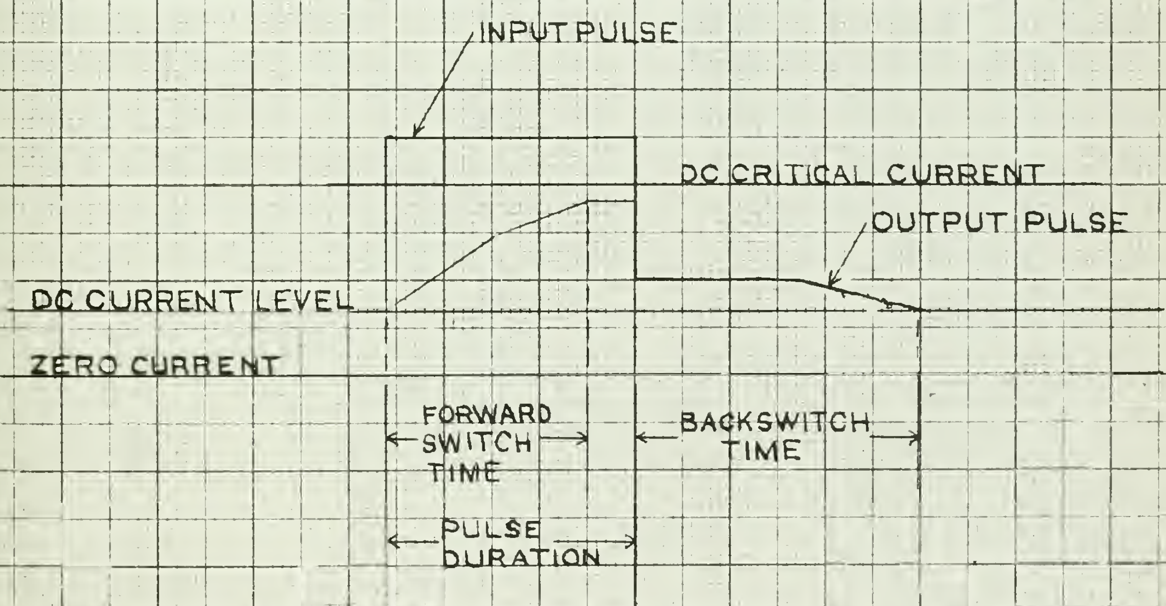


FIGURE 2

PHYSICAL APPARATUS DIAGRAM

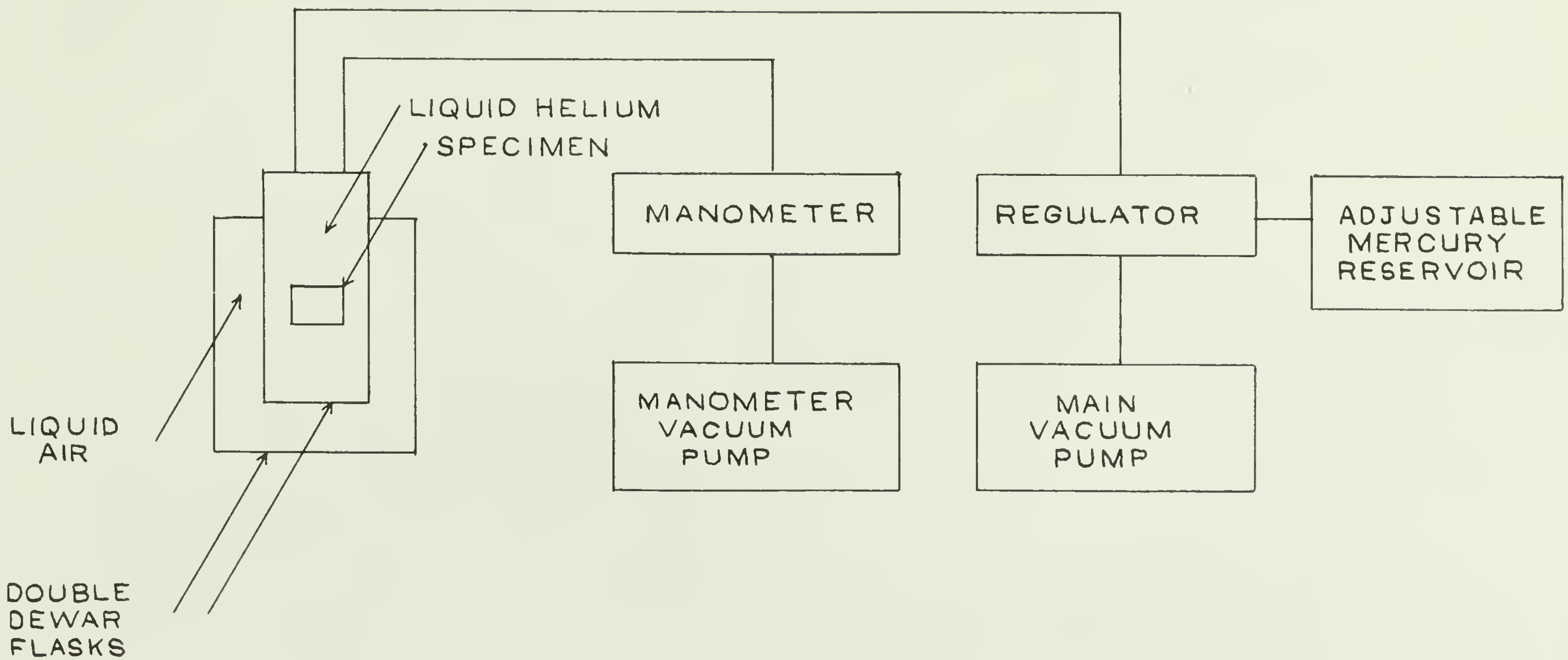


FIGURE 3

ELECTRICAL CIRCUIT

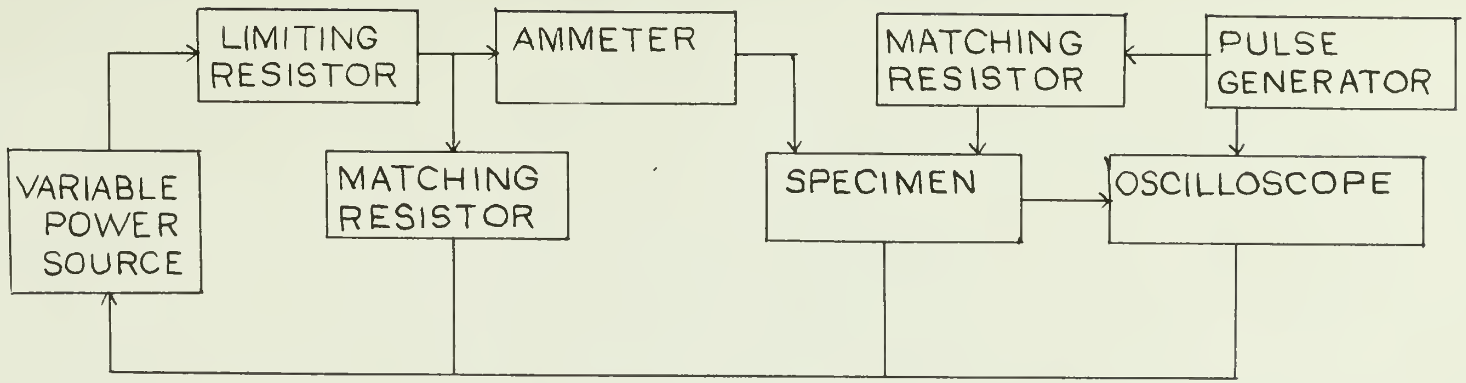


FIGURE 4

SPECIMEN HOLDER

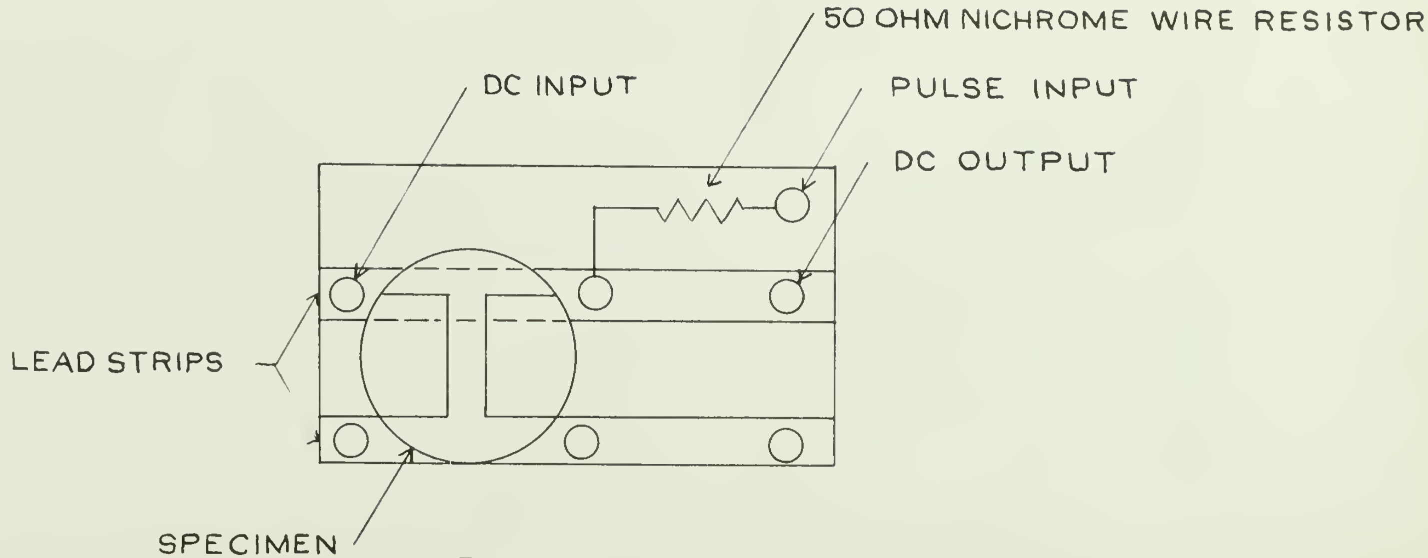


FIGURE 5

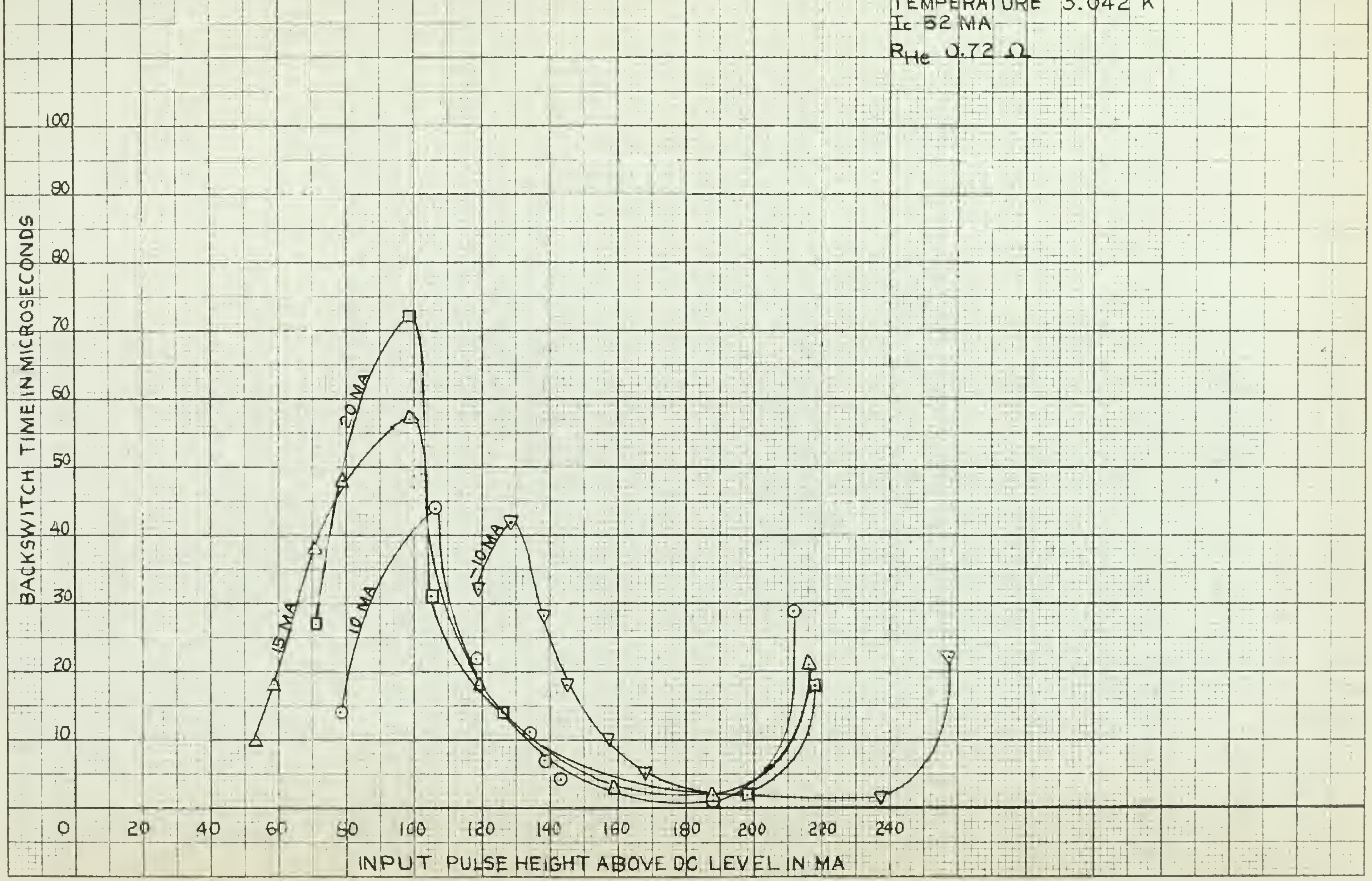
TABLE 1

DESCRIPTIONS OF THIN FILMS

Element	Width, microns	Thickness (mg)	Resistance, liquid He, ohms
60	60	80	0.72
64	60	40	1.75
84	62.5	160.5	0.364
G-145	60	80	0.413
Q-8	60	20	4.55 (quartz substrate)
Q-9	60	40	1.925(quartz substrate)
F&J-15	73	300	1.43
F&J-18	73	300	1.35

All the above elements were made from indium evaporated onto a glass substrate except Q-8 and Q-9 which were evaporated onto quartz, and F&J-15 and F&J-18 which were made of tin evaporated onto glass. The elements are numbered in accordance with their designations at the time they were made. The indium films were made at the Space Technology Laboratories, Inc., Hawthorne, California, and the tin films were made at the U. S. Naval Postgraduate School by C. S. Fong and R. Jacobs.

FIGURE 7



SPECIMEN60
TEMPERATURE 3.042°K
Ic 52 MA
RHe 0.72 Ω
BACKSWITCH TIME IN MICROSECONDS
100
90
80
70
60
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
200
220
240
INPUT PULSE HEIGHT ABOVE DC LEVEL IN MA
20 MA
15 MA
10 MA
-10 MA

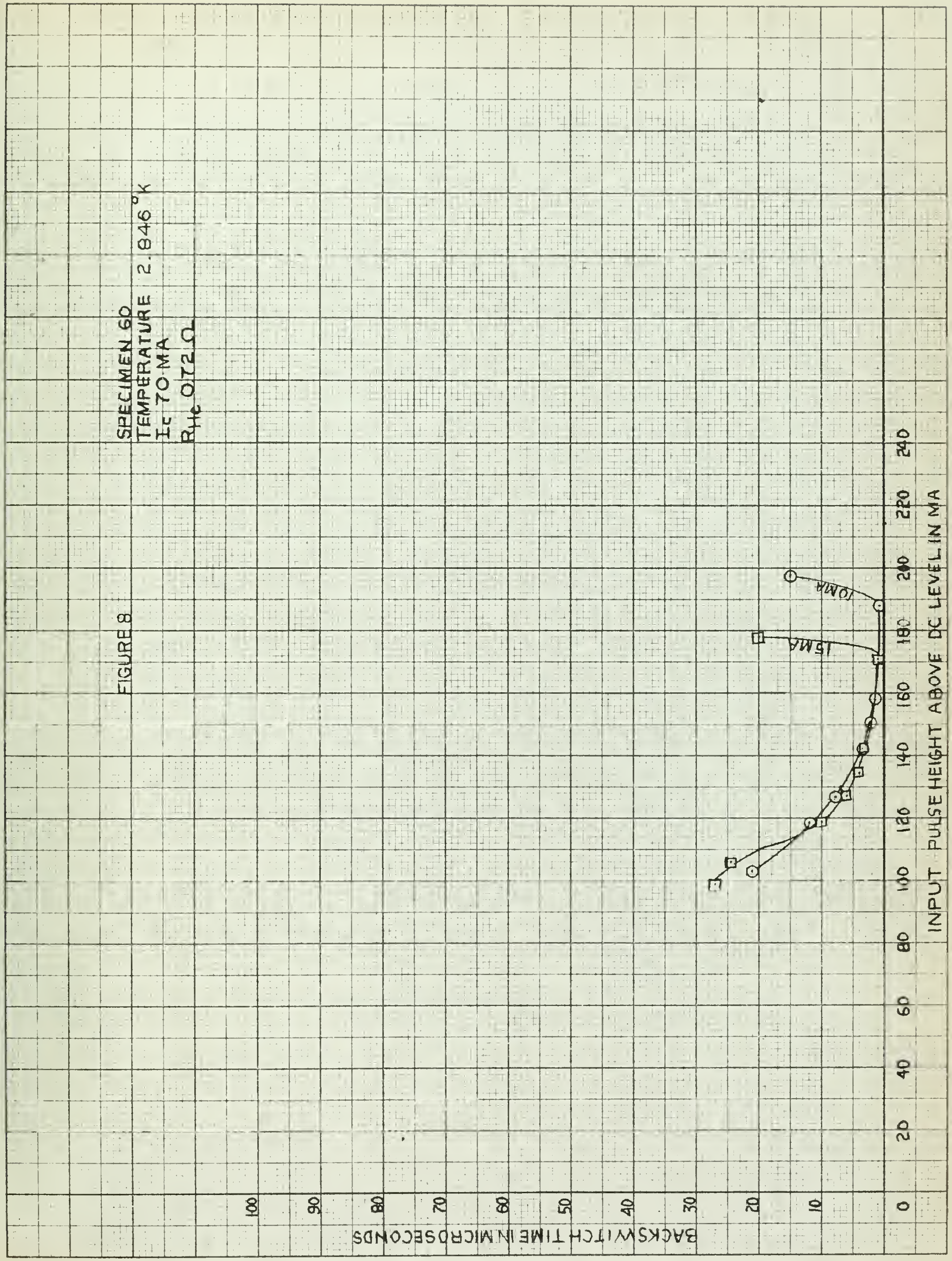


FIGURE 8
SPECIMEN 6D
TEMPERATURE 2.846 °K
Ic 70 MA
RHc .072 Ω
15MA
10MA
INPUT PULSE HEIGHT ABOVE DC LEVEL IN MA
BACKSWITCH TIME IN MICROSECONDS
0
20
40
60
80
100
120
140
160
180
200
220
240
10
30
50
70
90

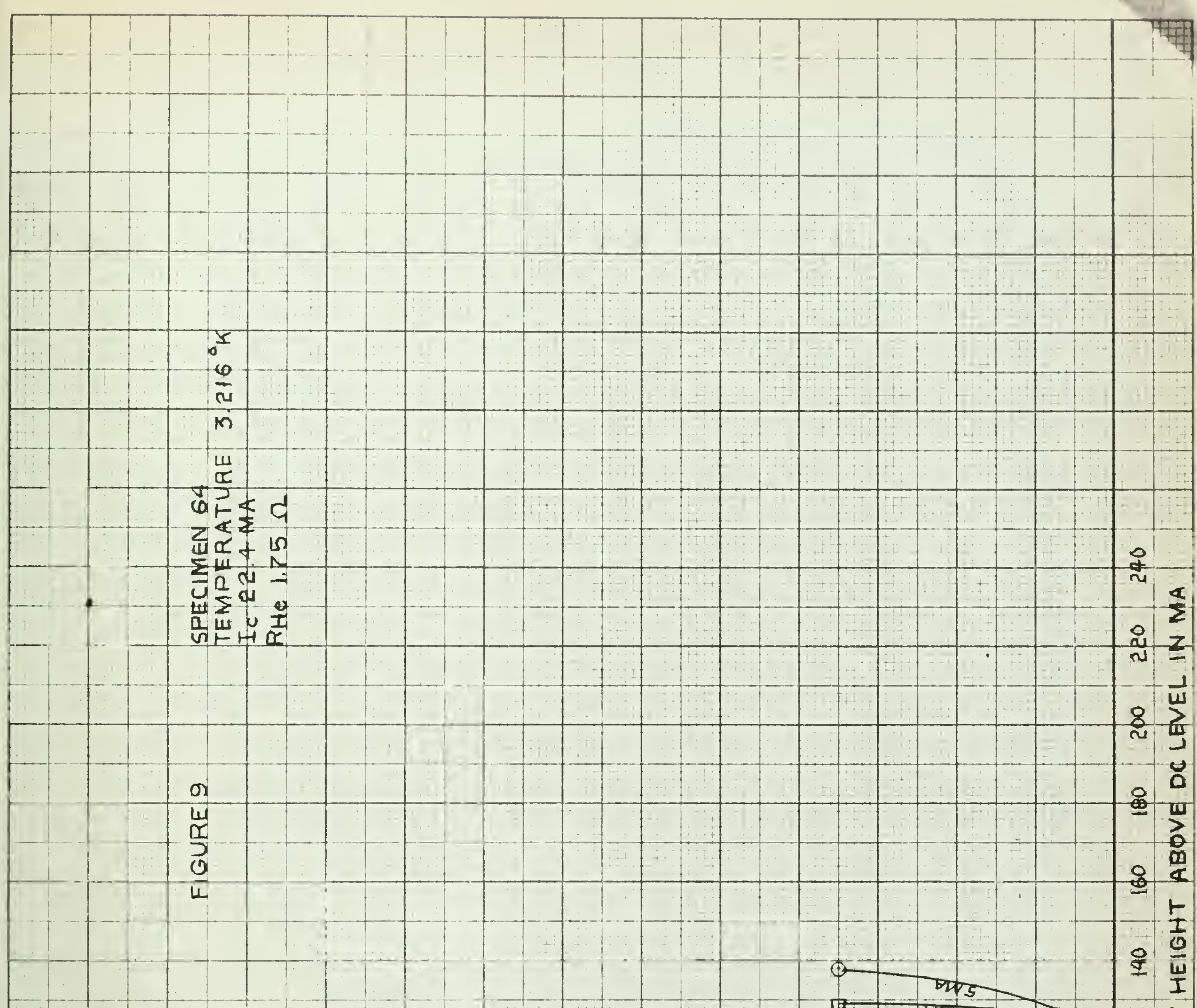


FIGURE 9
SPECIMEN 64
TEMPERATURE 3.216 °K
Ic 22.4 MA
RHe 1.75 Ω
5MA
10MA
BACKSWITCH TIME IN MICROSECONDS
INPUT PULSE HEIGHT ABOVE DC LEVEL IN MA
0
10
20
30
40
50
60
70
80
90
100
110
120
130
0
20
40
60
80
100
120
140
160
180
200
220
240

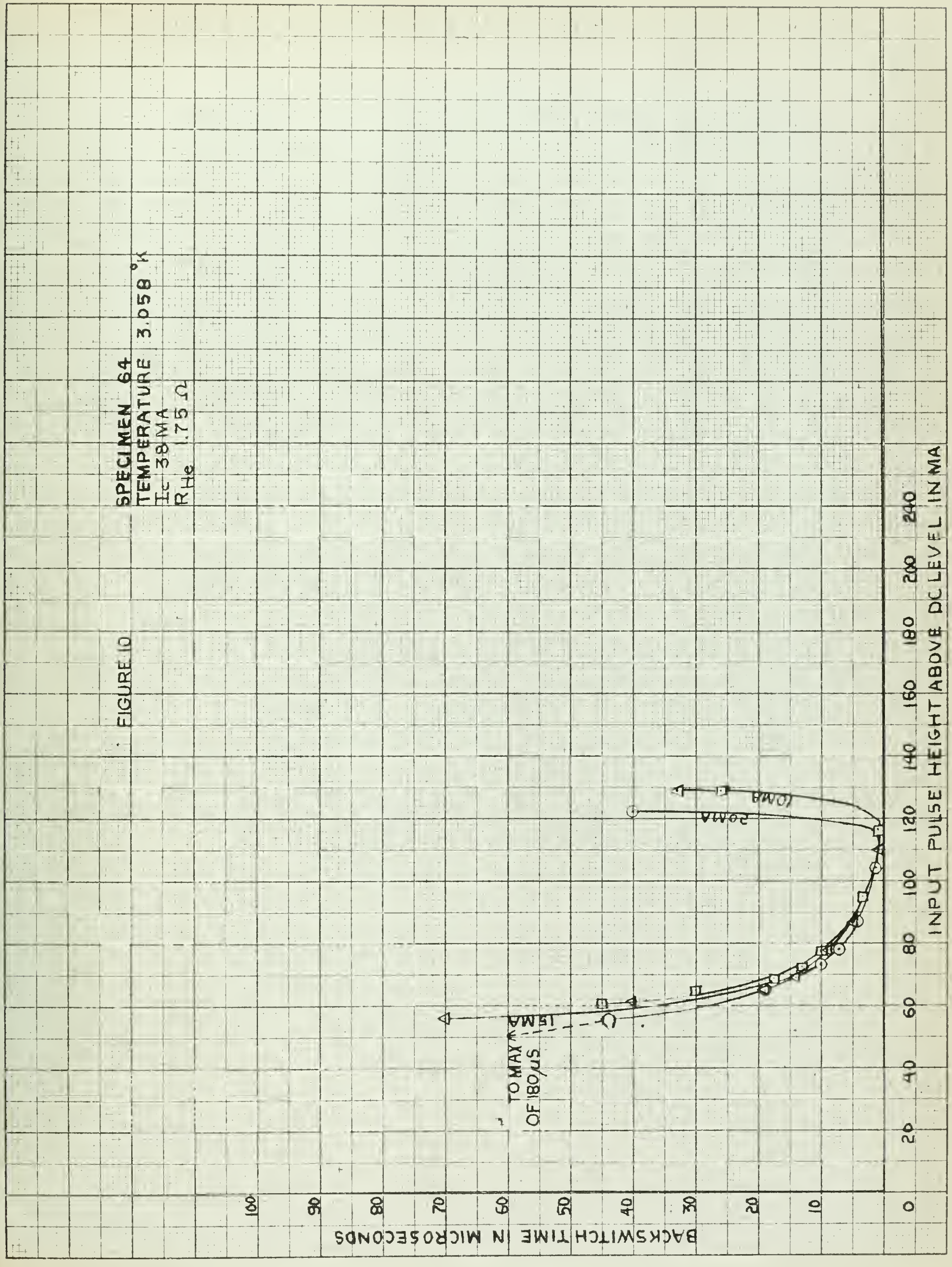


FIGURE 10
SPECIMEN 64
TEMPERATURE 3.058 °K
I_c 38 MA
R_{He} 1.75 Ω
BACKSWITCH TIME IN MICROSECONDS
INPUT PULSE HEIGHT ABOVE DC LEVEL IN MA
TO MAX OF 180 μS
15 MA
20 MA
10 MA
0
10
20
30
40
50
60
70
80
90
100
20
40
60
80
100
120
140
160
180
200
240

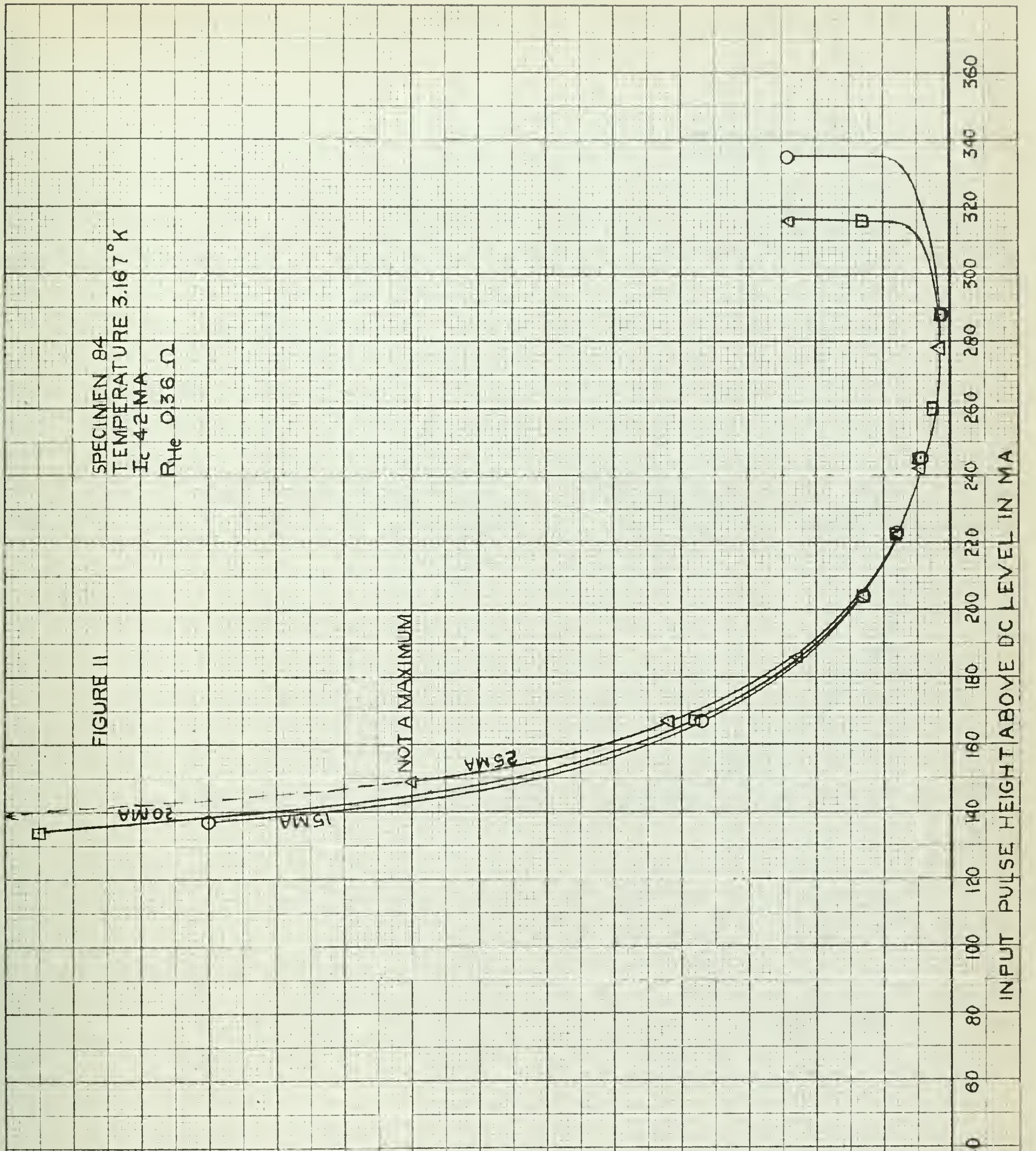


FIGURE 11
SPECIMEN 84
TEMPERATURE 3.167°K
I_c 42 MA
R_{He} .036 Ω
NOT A MAXIMUM
10MA
15MA
25MA
BACKSWITCH TIME IN MICROSECONDS
INPUT PULSE HEIGHT ABOVE DC LEVEL IN MA
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
160
180
200
220
240
260
280
300
320
340
360

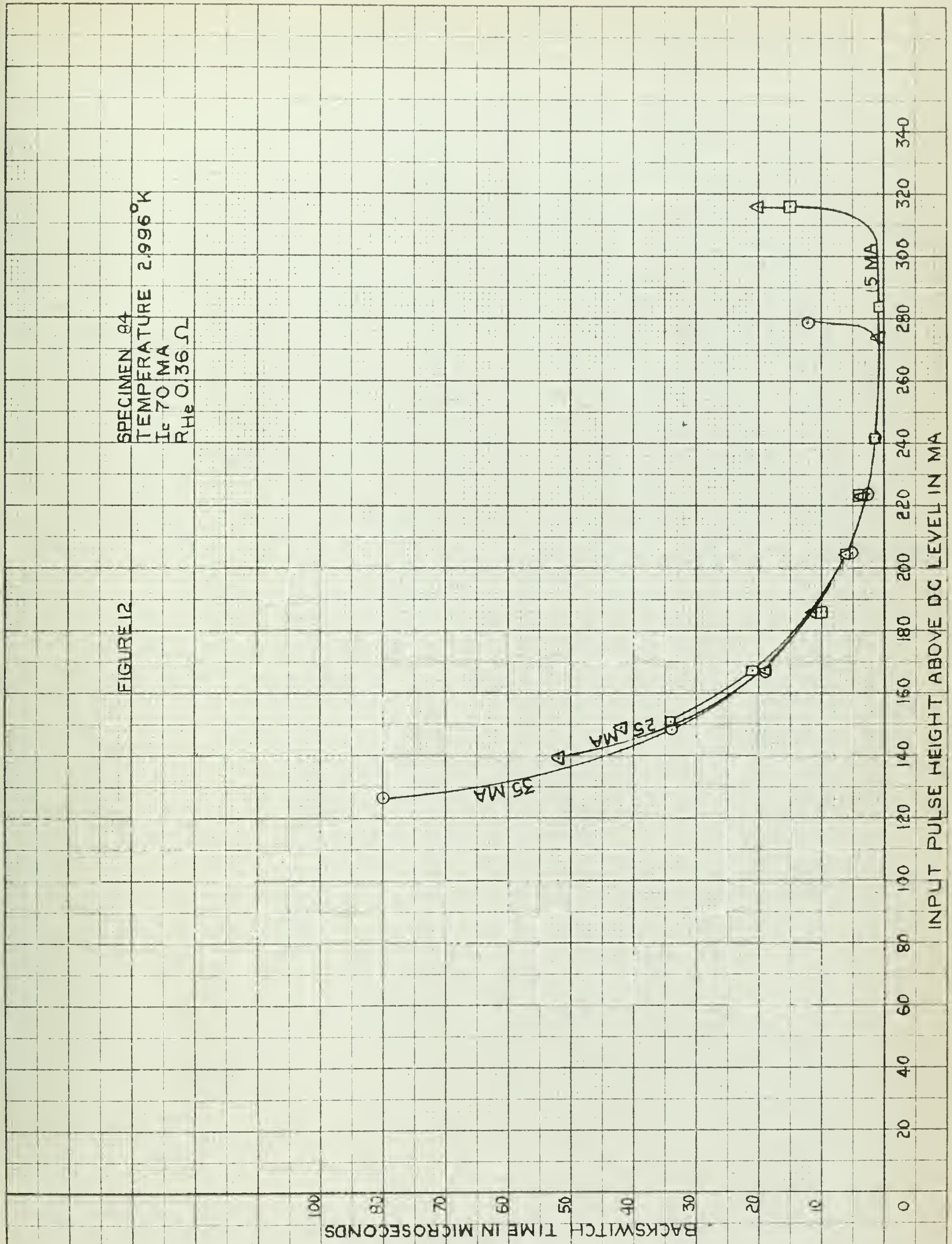


FIGURE 12
SPECIMEN 84
TEMPERATURE 2.996°K
I_c 70 MA
R_{He} 0.36 Ω
35 MA
25 MA
15 MA
INPUT PULSE HEIGHT ABOVE DC LEVEL IN MA
BACKSWITCH TIME IN MICROSECONDS
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340
10 20 30 40 50 60 70 80 100

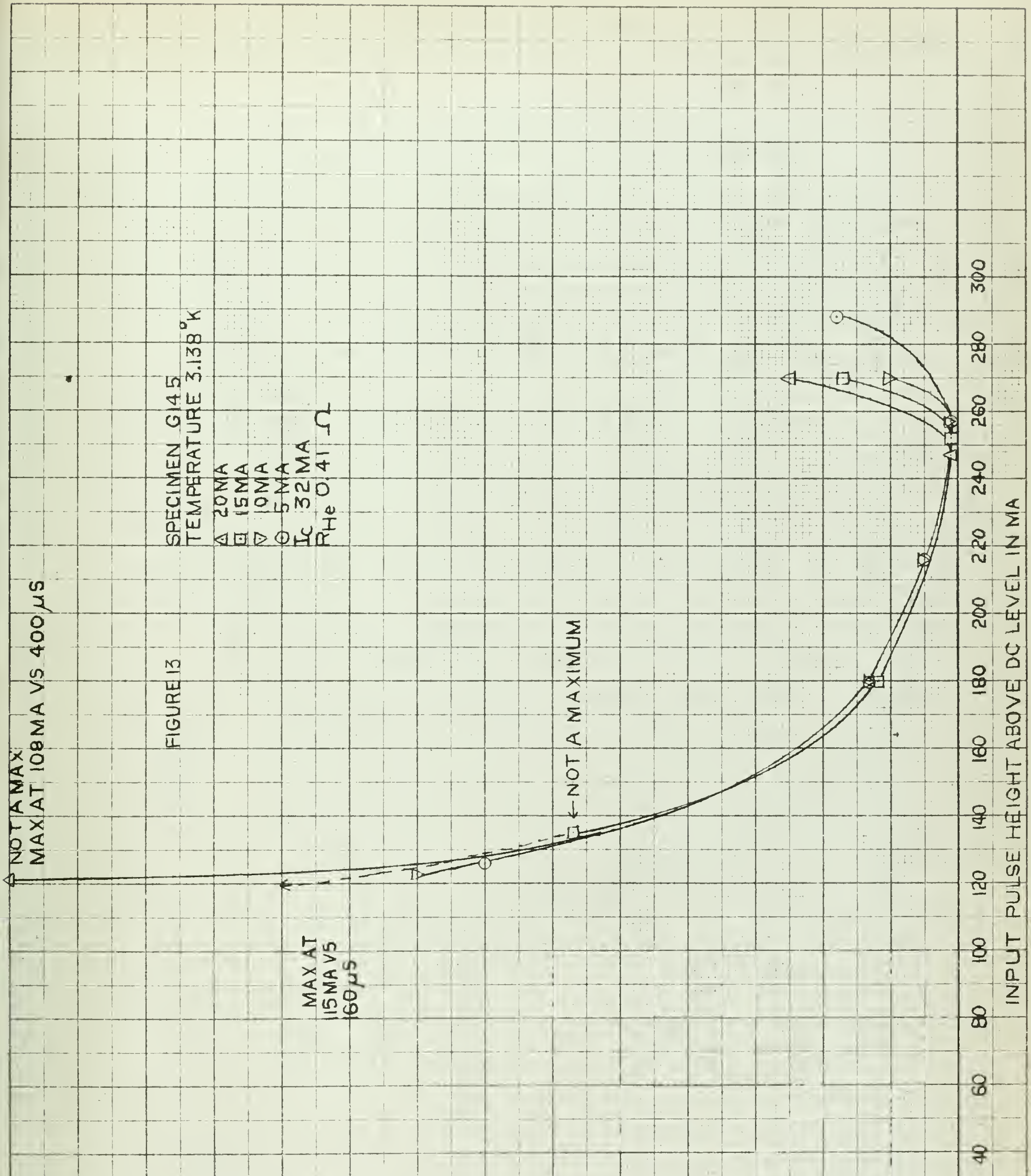


FIGURE 13
SPECIMEN G145
TEMPERATURE 3.138 °K
△ 20 MA
⊡ 15 MA
▽ 10 MA
⊙ 5 MA
I_c 32 MA
R_{He} 0.41 Ω
NOT A MAX
MAX AT 108 MA VS 400 μS
MAX AT 115 MA VS 160 μS
← NOT A MAXIMUM
BACKSWITCH TIME IN MICROSECONDS
INPUT PULSE HEIGHT ABOVE DC LEVEL IN MA
0
10
20
30
40
50
60
70
80
90
100
110
120
130
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300

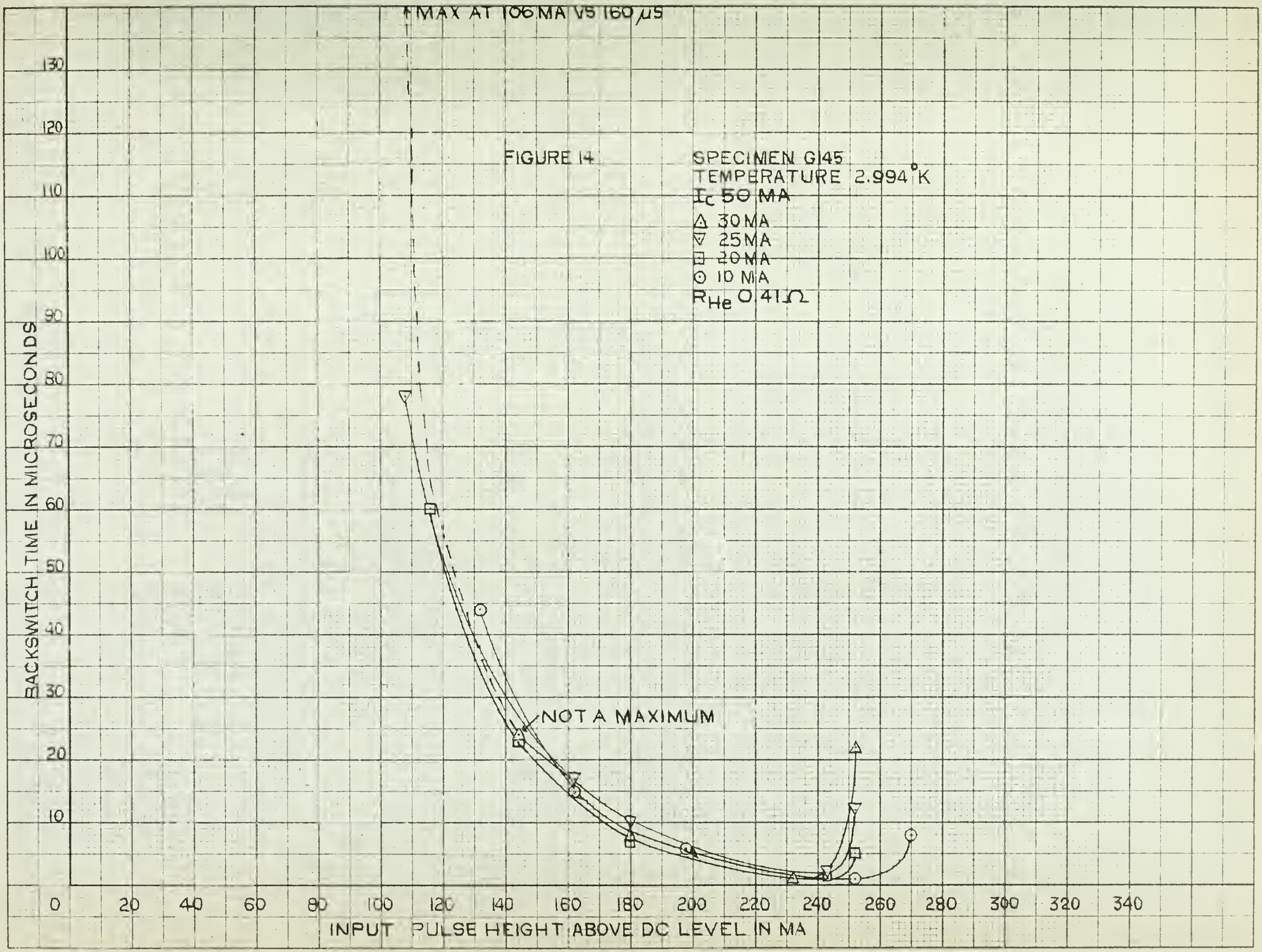

MAX AT 106 MA VS 160 μS
SPECIMEN G145
TEMPERATURE 2.994°K
Ic 50 MA
△ 30 MA
▽ 25 MA
⊡ 20 MA
⊙ 10 MA
RHe 0.41Ω
NOT A MAXIMUM
BACKSWITCH TIME IN MICROSECONDS
130
120
110
100
90
80
70
60
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
INPUT PULSE HEIGHT ABOVE DC LEVEL IN MA

FIGURE 14

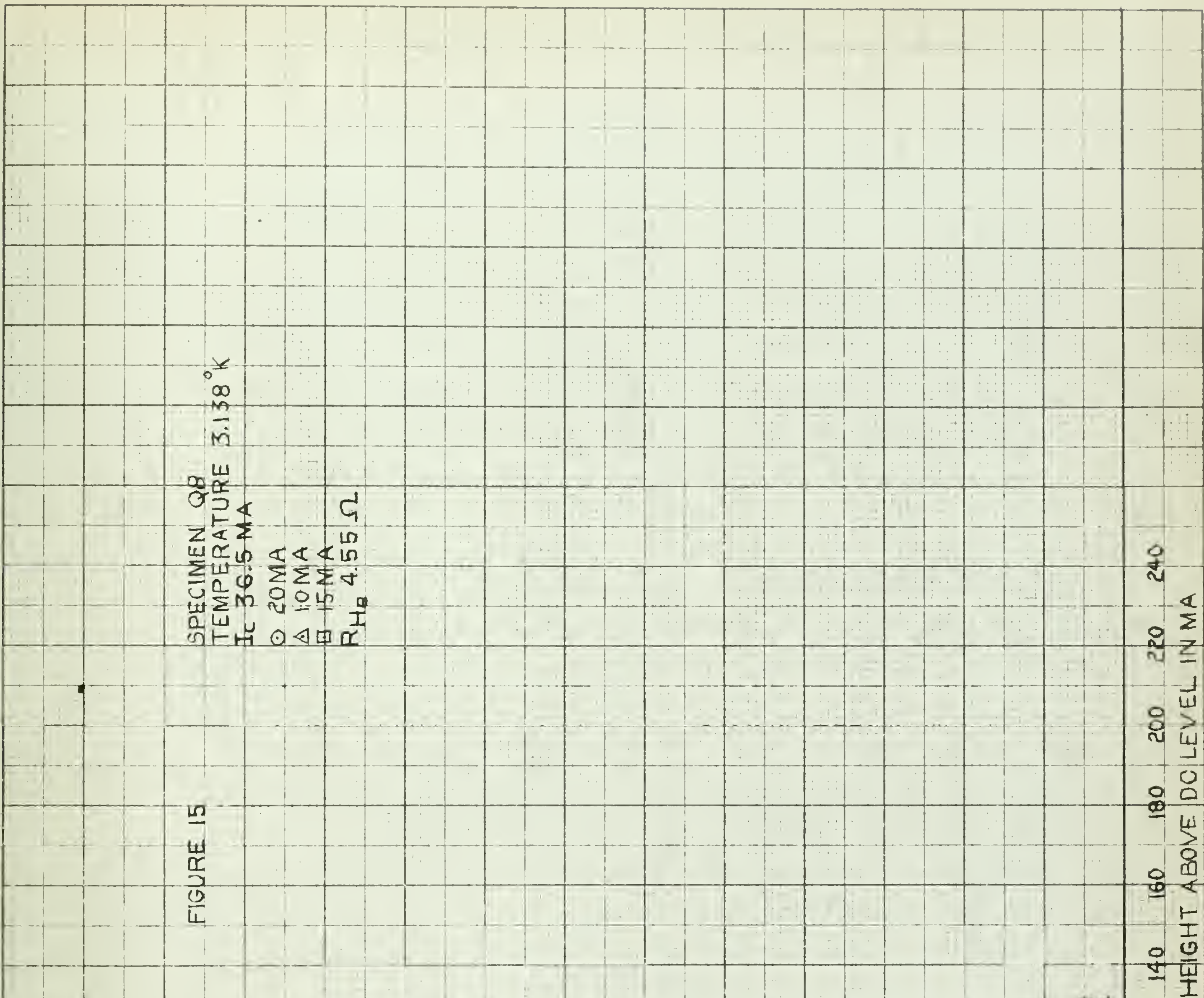
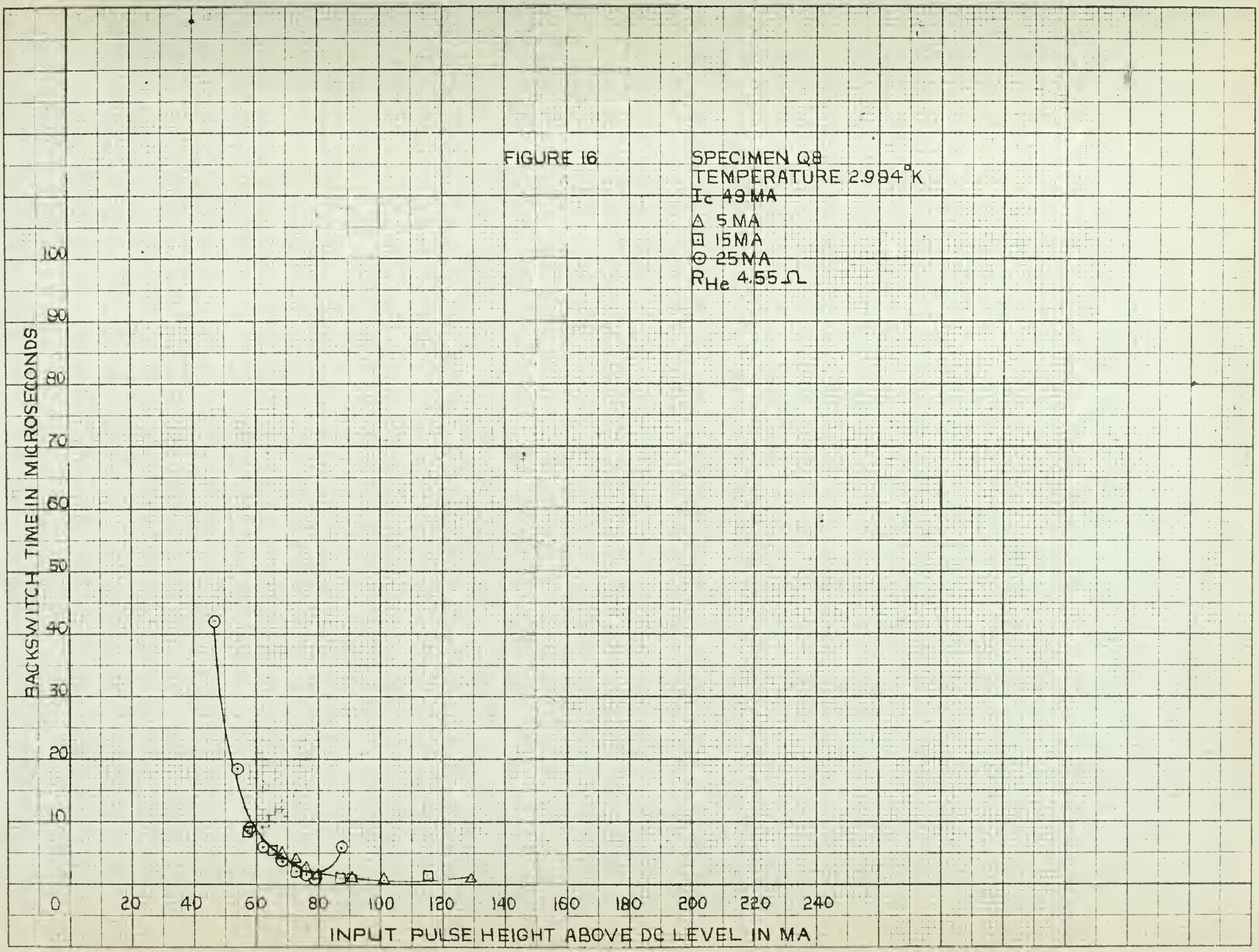


FIGURE 15
SPECIMEN Q8
TEMPERATURE 3.138 °K
Ic 36.5 MA
⊙ 20MA
△ 10MA
⊞ 15MA
RHB 4.55 Ω
BACKSWITCH TIME IN MICROSECONDS
INPUT PULSE HEIGHT ABOVE DC LEVEL IN MA
0 10 20 30 40 50 60 70 80 90 100
0 20 40 60 80 100 120 140 160 180 200 220 240

FIGURE 16


SPECIMEN Q8
TEMPERATURE 2.994°K
Ic 49 MA
△ 5 MA
⊡ 15 MA
⊙ 25 MA
RHe 4.55 Ω
BACKSWITCH TIME IN MICROSECONDS
0
10
20
30
40
50
60
70
80
90
100
20
40
60
80
100
120
140
160
180
200
220
240
INPUT PULSE HEIGHT ABOVE DC LEVEL IN MA

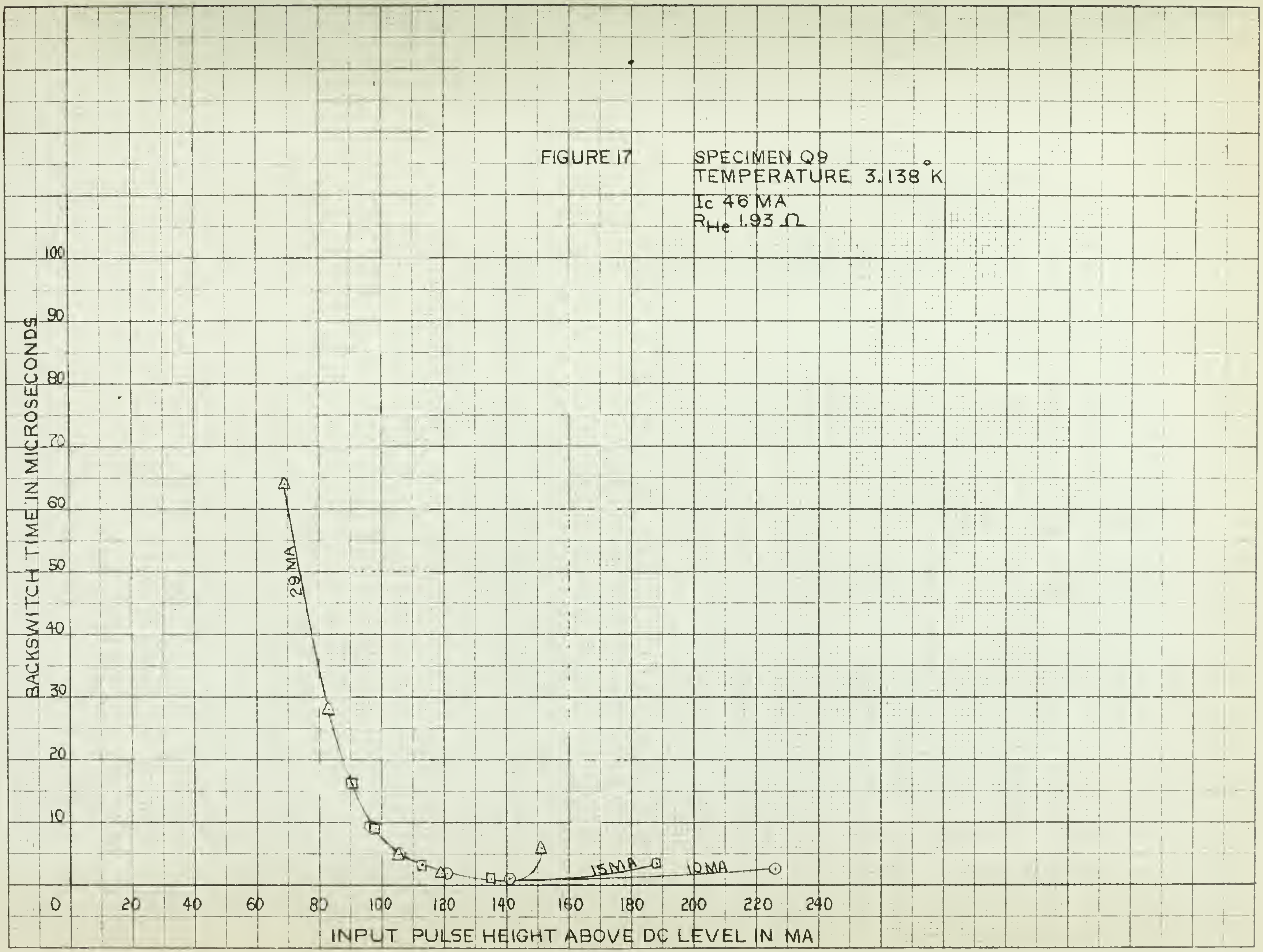

SPECIMEN Q9
TEMPERATURE 3.138 °K
Ic 46 MA
RHe 1.93 Ω
BACKSWITCH TIME IN MICROSECONDS
100
90
80
70
60
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
200
220
240
INPUT PULSE HEIGHT ABOVE DC LEVEL IN MA
29 MA
15 MA
10 MA

FIGURE 17

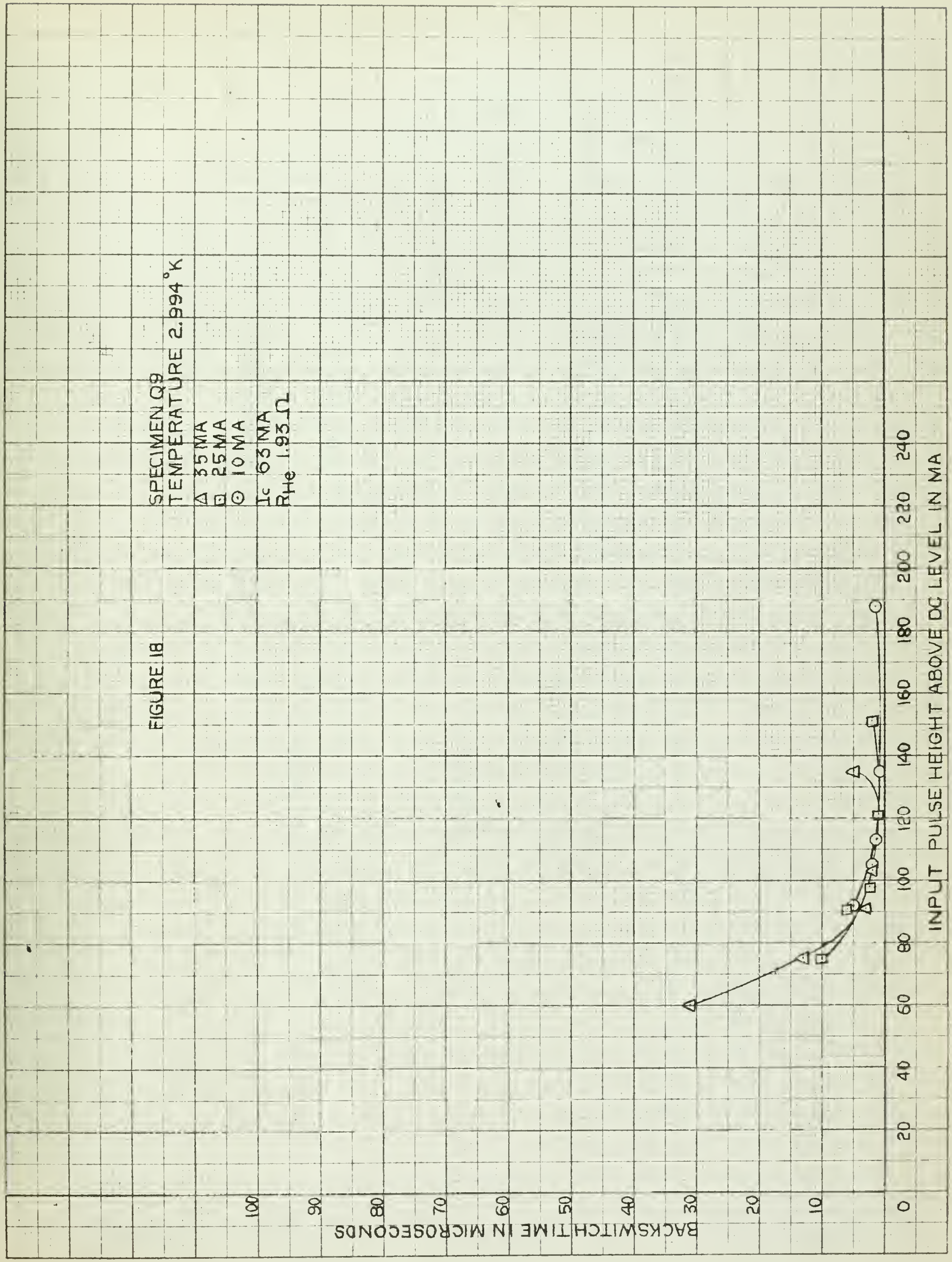

SPECIMEN Q9
TEMPERATURE 2.994°K
Δ 35 MA
⊡ 25 MA
⊙ 10 MA
Ic 63 MA
RHe 1.93 Ω
BACKSWITCH TIME IN MICROSECONDS
INPUT PULSE HEIGHT ABOVE DC LEVEL IN MA
0
10
20
30
40
50
60
70
80
90
100
120
140
160
180
200
220
240

FIGURE 18

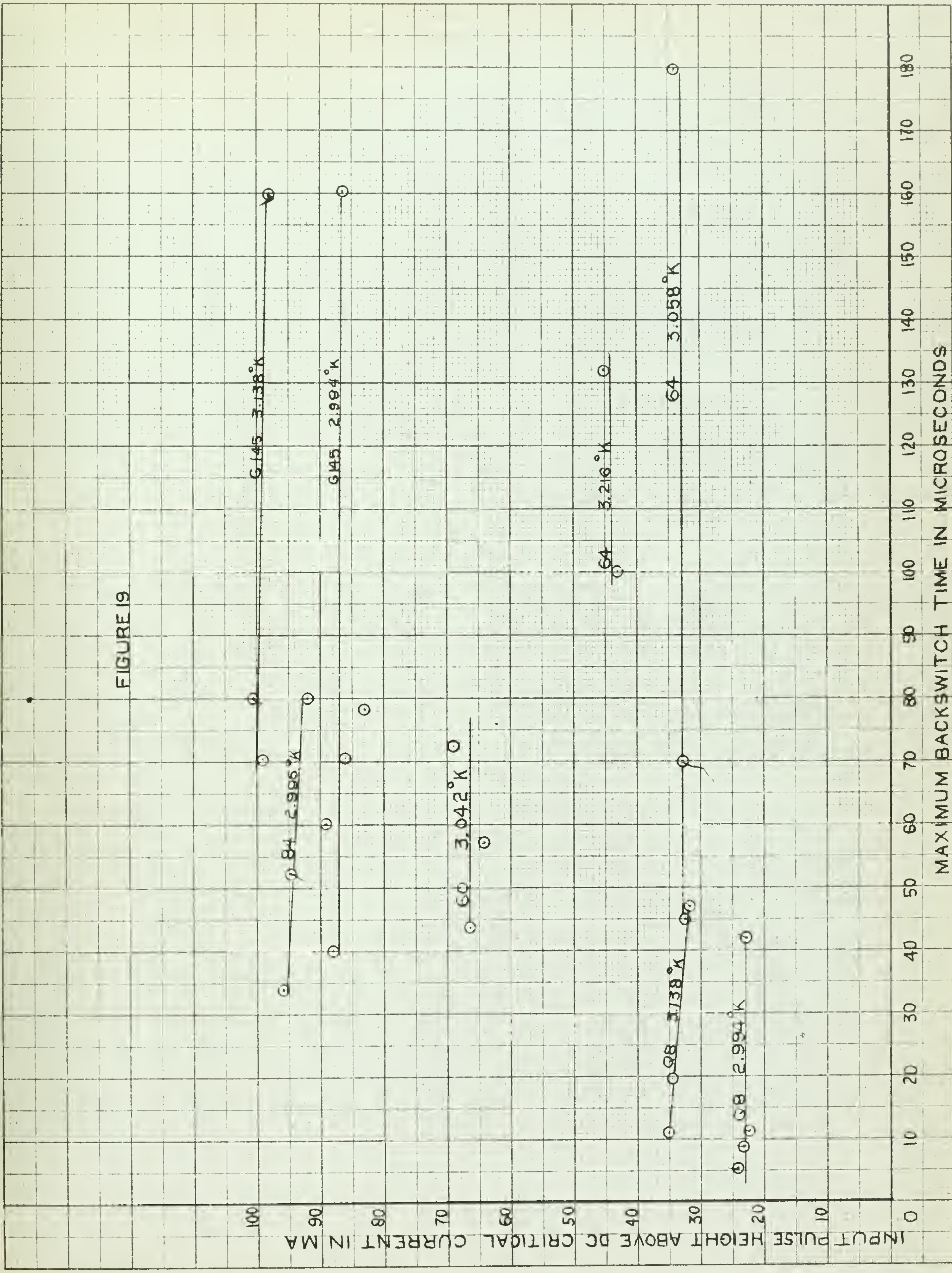

G 145 3.138°K
G145 2.994°K
84 2.996°K
60 3.042°K
64 3.216°K
64 3.058°K
Q8 3.138°K
Q8 2.994°K
MAXIMUM BACKSWITCH TIME IN MICROSECONDS
INPUT PULSE HEIGHT ABOVE DC CRITICAL CURRENT IN MA
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180

FIGURE 19